Vertical Land Movements in Coastal Areas around Northern and Baltic Sea within Germany

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Key words: vertical land movements, GNSS time series, multitemporal InSAR analysis, modeling of displacements

SUMMARY

The determination of vertical land movements in coastal areas is an emerging and prominent topic all over the world. In this research project it was possible to analyze GNSS time series and Sentinel radar data to estimate the actual vertical movement rates for coastal areas within Germany.
In total, GNSS data sets from 180 permanent stations between 2010 and 2016 were pre-processed, evaluated and analyzed; applying an innovative approach for stability check of stations, it was possible to reference the results of these time series to stable zones in low mountain ranges, about 200 km apart from the coast.
Additionally, Sentinel-1 radar data sets from 2014 to 2019 were independently processed using the Persistent Scatterer (PS) methodology, resulting in an area-wide motion field for the study area.
For numerical modelling of the velocity field a functional model was applied (no-mesh concept), based on position-related radial-basic-functions (RBF) and allowing the combination of clustered radar data and GNSS-time series.
As final result for the period of investigation the vertical movements in the areas close to the Northern and Baltic Sea in Germany were computed and compared with external knowledge resp. influence factors.

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1. INTRODUCTION

The mean water level in the Northern Sea has risen by about 7 m in the last 7000 years, mainly due to (Post)-Glacial Isostatic Adjustment (GIA) after the last Ice Age in this area, driven by a lot of further natural and anthropogenic climate changes and local effects, see e.g. Jensen (2020). For vertical land movements aside of GIA and regional tectonics, several more local sinking and rising effects can be encountered, due to groundwater withdrawal, gas- and oil extraction and punctual construction resp. mining activities.
In a former project, named IKUES (Wanninger et al. 2009), the vertical land movements were derived for Lower Saxony, based on an analysis of existing levelling networks and – in that period – limited GNSS data series on permanent stations in this federal state. Here an attempt is made to derive the actual vertical movement rates for all coastal zones of the Northern and Baltic Sea within Germany.
As data source GNSS data sets from 160 permanent stations between 2010 and 2016 were evaluated and analyzed applying an innovative approach, see section 2.2, so that these time series can be referenced to stable zones in the low mountain ranges and it is justified to characterize the resulting movement rates as "absolute".
Additionally Sentinel-1 radar-data sets from 2014 to 2019 were independently processed using the Persistent Scatterer (PS) method.
Levelling data were not included in this analysis, as we wanted to derive the movements valid for the last decade, and here not enough levelling data sets were available.
Methodically, the approaches for modelling a velocity field from the IKUES project (Wanninger et al., 2009) were extended for the inclusion of radar data, which required a clustering of the PS. For the surface approximation itself in the former project position-based radial basis functions (RBF) were used. This concept was extended by time-related RFBs to be able to map non-linear temporal changes in the vertical velocities.

This research project is embedded into a joint project, see acknowledgement, where the final objective was to derive so-called "absolute" mean-sea-level changes, i.e. solid information with reference to geologically stable zones. Here just the subproject to derive absolute vertical land movements is discussed.

2. GNSS DATA AND ANALYSIS

2.1 Available data and pre-processing

The location of the included 160 permanent GNSS-stations is depicted in Fig. 1. Analyzed were mainly SAPOS-stations of the federal state survey departments in Germany and 21 GNSS-stations belonging to IGS, EUREF and GREF services. In addition 19 GNSS-stations were included, which are positioned directly on tide gauges; they serve as link to the - here not discussed - derivation of mean-sea-level changes.
For all these GNSS-stations RINEX-data were collected, harmonized and then analyzed to achieve time series for the variability of the 3 coordinate-components of each station. A harmonization was necessary, as the storage concepts in the different federal states were very different: Some data were collected in a 1 second interval, others reduced to 30 second. Aside, the numbering of the data-sets was different and some were packed, others not. All together about 10 TByte of data had to be processed and analyzed.
After this pre-processing RINEX-data with 30 second interval were derived, which were then processed using the software WaPNet, developed by WaSoft company, Dresden. Antenna corrections, precise ephemeris data and atmospheric information (from ESA) were included into the processing chain.

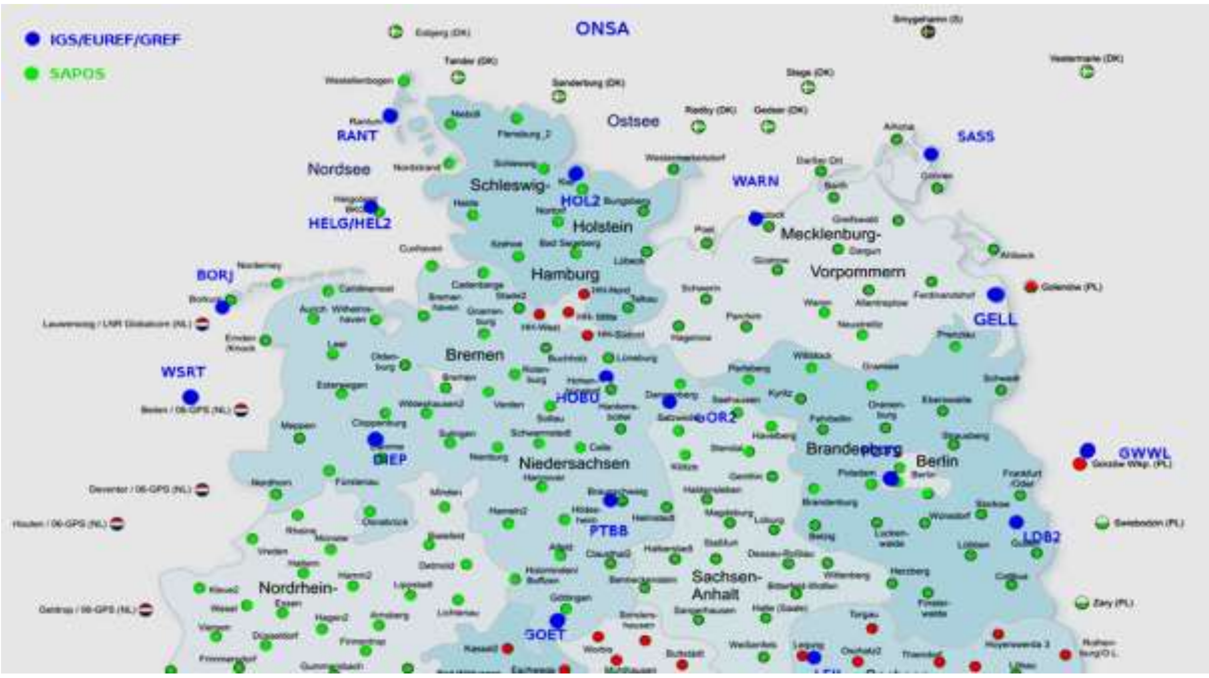

Figure 1: Location of GNSS permanent stations included in this project. Aside of SAPOS stations the reference group with IGS, EUREF and GREF stations are depicted.

To allow for internal checking, the processing was done in steps: For each day the RINEX-data were processed in 5 groups, the western, middle and eastern section of SAPOS stations. the 4th group are the tide gauge stations together with selected stations in their neighborhood; the 5th group is the reference group, highlighted in Fig. 1 and formed by IGS, EUREF and GREF stations, selected stations together with selected stations in the research area.
Per day a set of 3D-coordinates was computed inclusive their covariance-matrix for each of these 5 groups. The 35 partial solutions per week were then combined in a free network adjustment using the software package PANDA, developed by Geotec GmbH, which allows to include 7 similary parameters between each coordinate set. This concept allowed us to get a good impression on the internal precision of the resulting 3D-coordinate sets per week.

2.2 Connection to stable areas

To derive "absolute" vertical displacements, it is necessary to relate all coordinate estimates to areas, which can be expected to be geologically stable. For this project we considered the low mountain ranges in the northern part of Germany as such a "stable area". This is in coincidence with former studies on vertical movements and fits to the definition of fundamental levelling stations by the federal surveying agencies in Germany, see the location of *Wallenhorst, Flechtingen* and *Hoppegarten* in Fig.2.

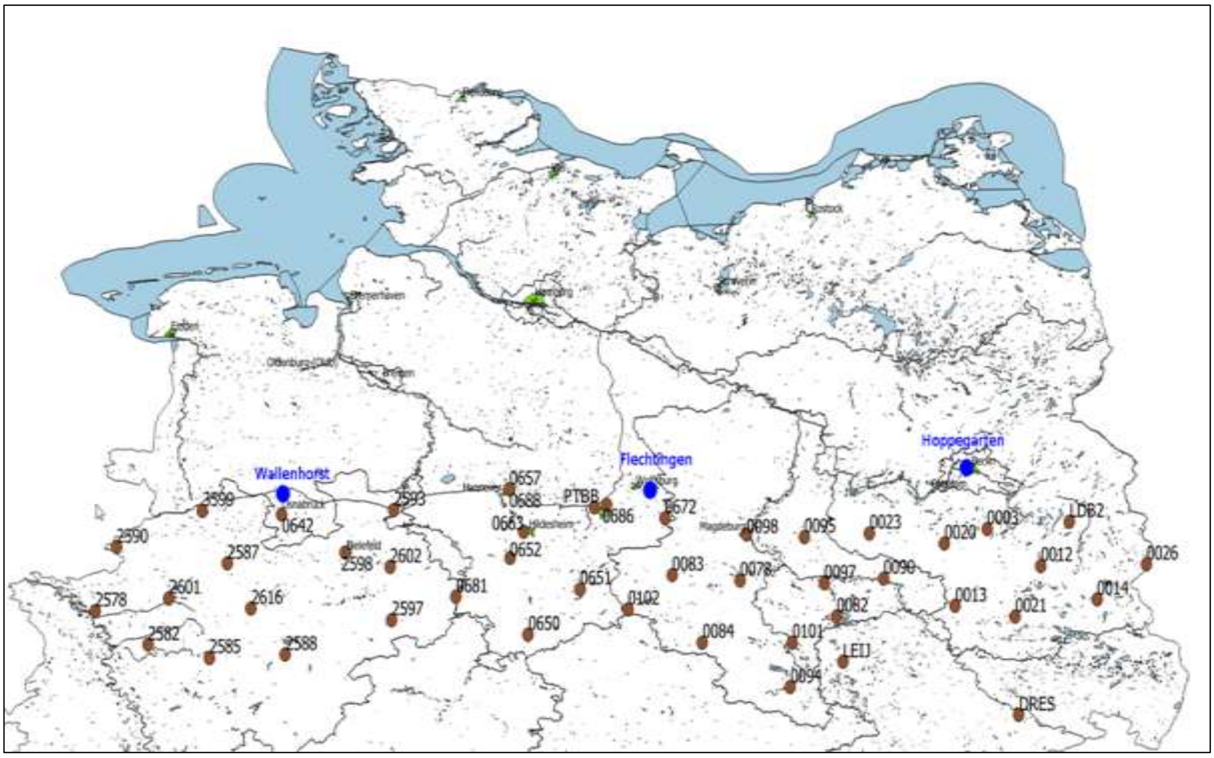

Figure 2: Position of GNSS-reference stations in the low mountain ranges, located in a geologically "stable area". In blue the locations of fundamental levelling stations are depicted.

At the beginning 46 GNSS-stations in this area were selected to serve as potential reference stations for the derivation of absolute vertical land movements in the coastal areas.
By an innovative data driven approach (Tengen et al. 2019), it is possible to analyse the coordinate time series of these potential reference points on significant displacements. This methodology is based on subsequent two-epoch comparisons, i.e. a rigorous congruency test~~, i.e.~~ with inclusion of the covariance matrices, of each epoch to the zero-epoch, here the starting epoch in 2010.
In Fig. 3 the principle of this approach is depicted in a simplified way: After the analysis of several epochs for each station a time series is available, here presented just for the horizontal components. The new analysis concept consists of two steps: At first by classical congruency testing the indentity of the network geometry between epochs is tested; then one tries to drive a movement pattern for the unstable stations. In Fig. 3 for station 1 a linear movement could be identified, for station 8 an offset between epochs 2011 and 2012 is analysed and for station 3 an irregular movement is encountered. For the remaining stations, located within the grey area, small irregularities are found, but all are below the level of significance, i.e. they can be considered as beeing congruent.

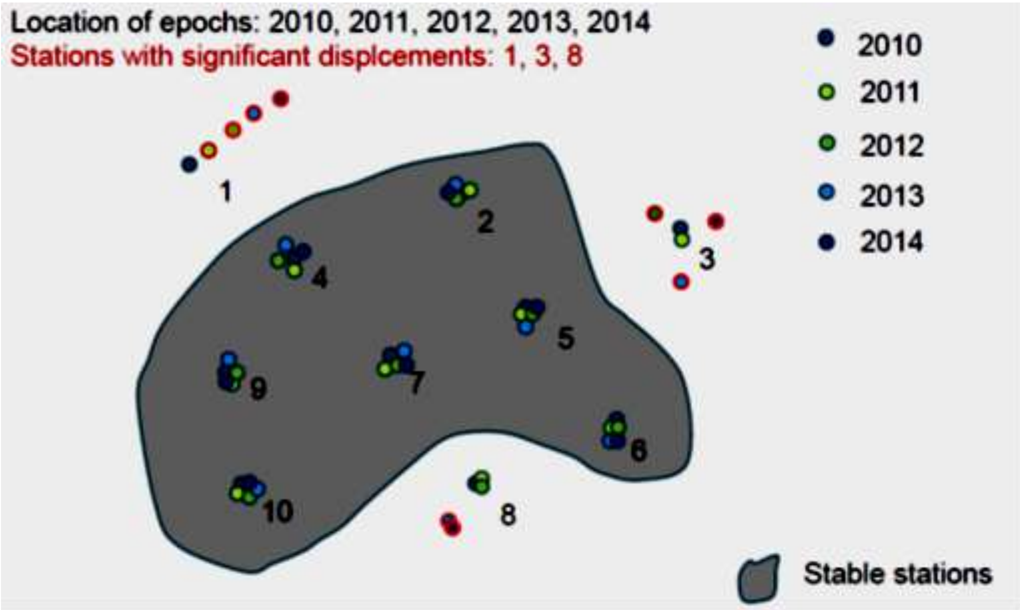

Fig. 3: Extension of the classical congruency tests to derive movement pattern out of the analysis of several epochs (Tengen et al., 2019)

If a reference station has significant movements, but the movement pattern can be described by parameters, this station can remain in the set of reference stations. This concept has the big adventage, that even in the analysis of extensive and long-term monitoring projects with a lot of data sets, where several disturbencies and local effects can be found, the group of reference stations can be kept to be sufficiently large.
By this approach it was possible to keep a sufficent number of GNNS-stations within the group of reference stations, even if they had some movement pattern.

3. SENTINEL-1 RADAR DATA AND ANALYSIS

3.1 Available data sets

As data sets for radar interferometric analysis Sentinel-1 data were available, mainly 133 scenes of track 139 in descending orbit from Oct. 2014 to March 2018 for the North sea coast and the western part of the Baltic Sea and130 scenes of track 146 in ascending orbit from Oct. 2014 to Sept. 2018 for the main part of the Baltic Sea.
To analyze these data the Persistent Scatterer Interferometry (PSI) method was applied, first developed by Ferretti at al. (2001). Even if several areas have a rural character with just a few infrastructure objects and a lot of vegetation, it turned out that PSI was advantageous compared this the Small Baseline Subset (SBAS) method, see the discussion in Niemeier et al. (2021).
Due to our limited computer capacity, we analyzed the radar data by a subdivision in patches with 20 km stripes of overlaps, see Fig. 4. By analyzing these patches, a complete coverage of the coastal areas was possible (Riedel et al., 2019).

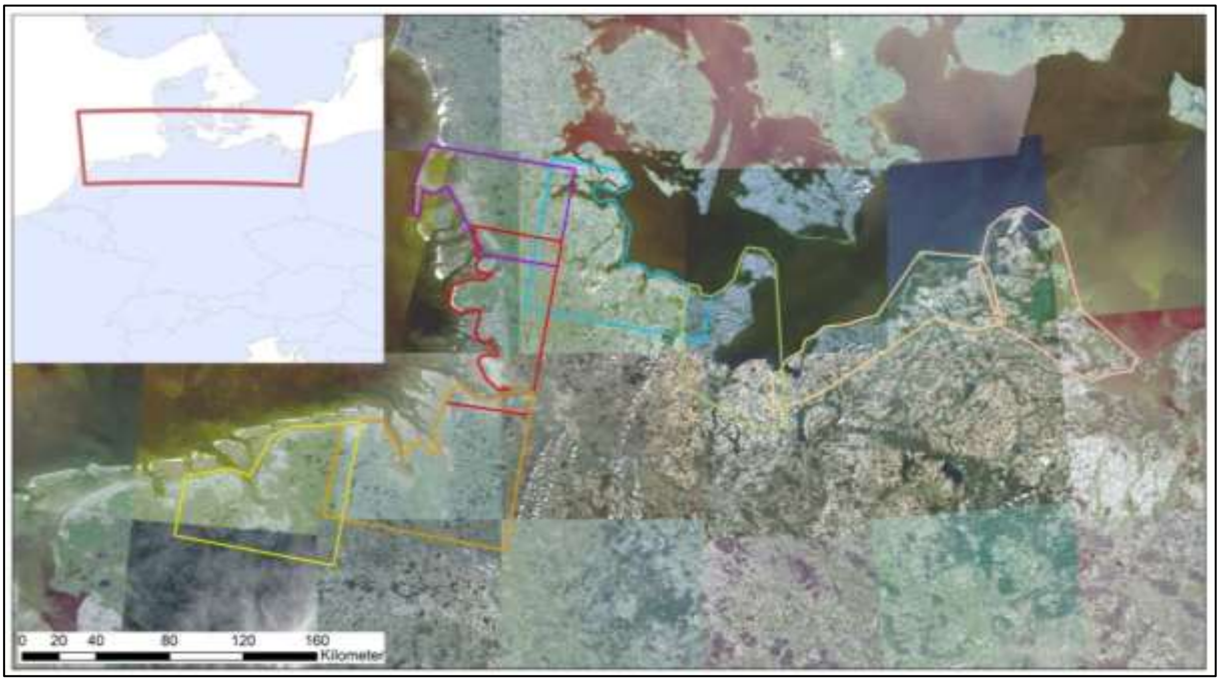

Fig. 4: The selected patches with Sentinel-1 radar data, processed with PSI-methods.

3.2 Results of PSI-analysis

The vertical movements for the complete study area are depicted in Fig. 5. The results of the individual patches were put together, what is jusified, as the processing of the overlaps did not give any hint on remaining systematic effects between the patches resp. tracks, derived differences were below 0.7 mm/a.

The original line-of-sight results (LOS) were transfered to vertical displacements, neglecting possible horizontal movements, what seems to be justified in this area. Finally, just a linear displacement model was assumed, as no information on non-linearities were available.
The results indicated a mainly homogeneous velocity field for most areas at the Northern and Baltic Sea with velocities between ± 2mm/a, leading to the conclusion that these areas could be considered as being stable in this relatively short time intervall of about 4 years.

But some specialities were detected:

- Close to the border of the Netherlands, i.e. in the surrounding of the city of Emden stronger subsidence was detected, up to - 8 mm/a. This subsidence might be associated with the long-lasting gas extractions in the Groningen Gasfield.
- More East, around Wilhelmshaven and Etzel strong subsidence up to -10 mm/a was detected, which can be related to several storage caverns in the underground.
- In the East,in Rostock local sudsidence could be related to extensive construction activities in the harbour.

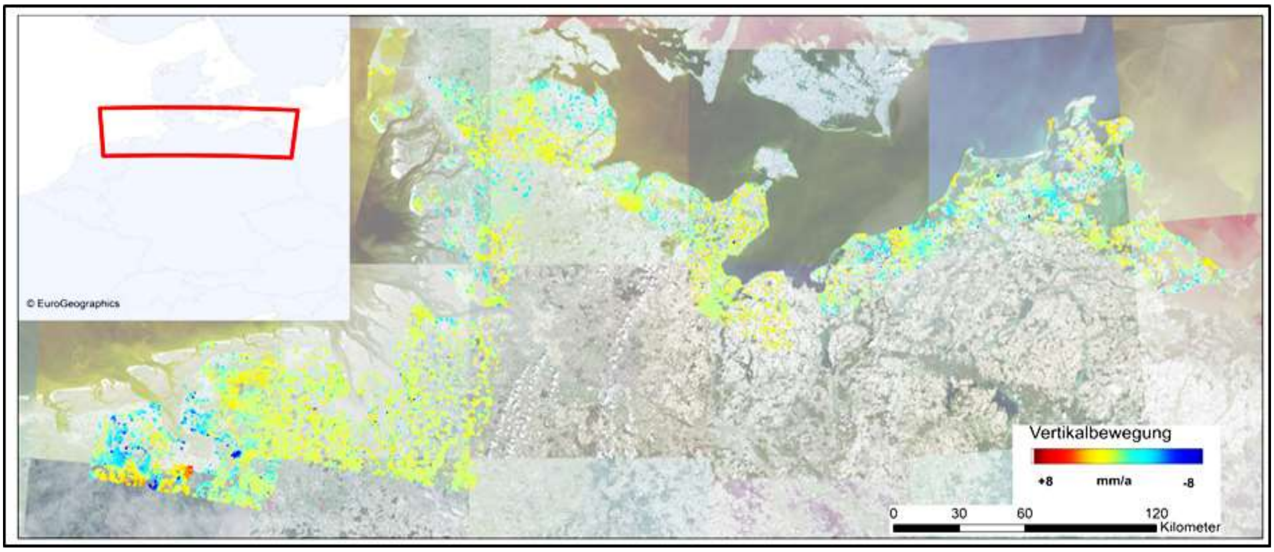

Fig. 5: Combined result of the PSI-analysis for the coastal areas of Northern and Baltic Sea in Germany, derived as linear model for the time span Oct. 2014 to Febr. 2019.

In general, the results around the Baltic Sea are more homogeneous than in the western section. In Fig. 6 the PSI results are combined with rates of potential post-glacial ublift in that area, see Frischbutter and Schwab (2001), following the geoscientific principle of Glacial Isostatic Adjustment (GIA). The PSI results can not be used as proof of these GIA-related uplift rates, the time series of 4 years is too short for that; but the tendency goes in the same direction.

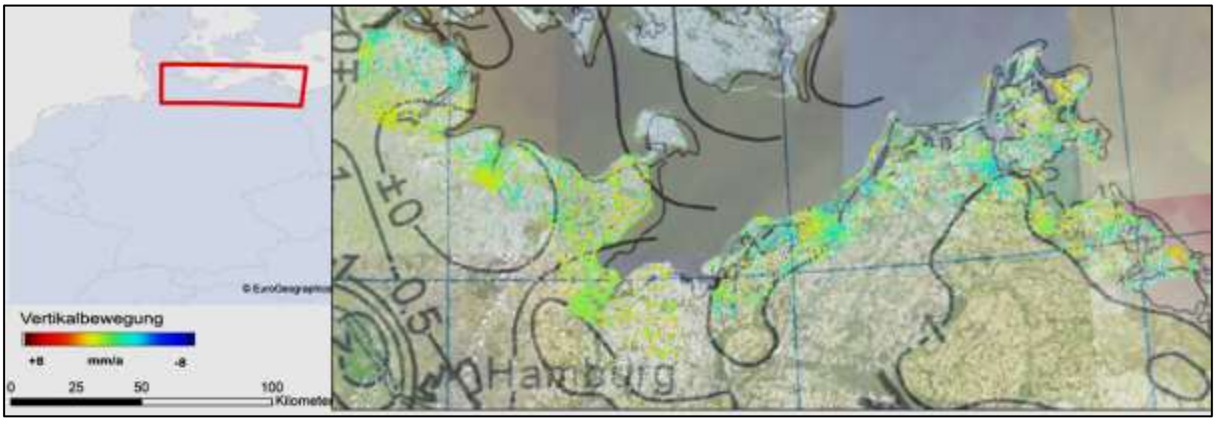

Fig. 6: Comparison of PSI results and uplift rates of Global Isostatic Adjustment
(Frischbutter and Schwab 2001)

4. MODELLING OF VERTICAL MOVEMENTS

4.1 Methods

The higher-level objective of this research project was to derive a time-dependent velocity model for for vertical movements in the research area.
To achieve this goal, in principle different mathematical concepts can be followed. Here a so-called no-mesh approach was followed, where the velocity field was approximated by linear combinations of radial basis functions (RBF), which have proven their suitability for such problems (e.g. Buhman 2003). The RBFs are distributed in the research area and allow the computation of velocities for arbitrary positions in the area. Criteria for the position and of a RFB is the availability of data and the expected velocity resp. local variability of the velocity, what has influence on the individual sphere of action of each RBF.
Here just ”position based RBFs” were used, as the data range was restricted to just a few years, but in principle ”temporal RBFs” can be used as well, to account for time dependent variabilities within the velocity field, see Niemeier et al. (2021).
The applied methology is similar to the approach used in the former ”IKUES” project (Wanninger et al., 2009), the main extension is the possiblity to include PSI data. All original PSI results were including in the processing chain, just to define the best RBF positions a clustering was performed. to account for the often high point density of the PSI stations.

4.2 Modelling with GNSS Data

In Fig. 7 results for an areal approximation of velocities are presented, derived out of GNSS time series for the years 2010 – 2016. These velocities are related to the ”stable” reference station in the low mountain ranges following the approach given in section 2. Due to the short time period for the observations, just a linear velocity model could be justified, i.e. the approximation is performed by position based RBFs, only, see section 4.1.

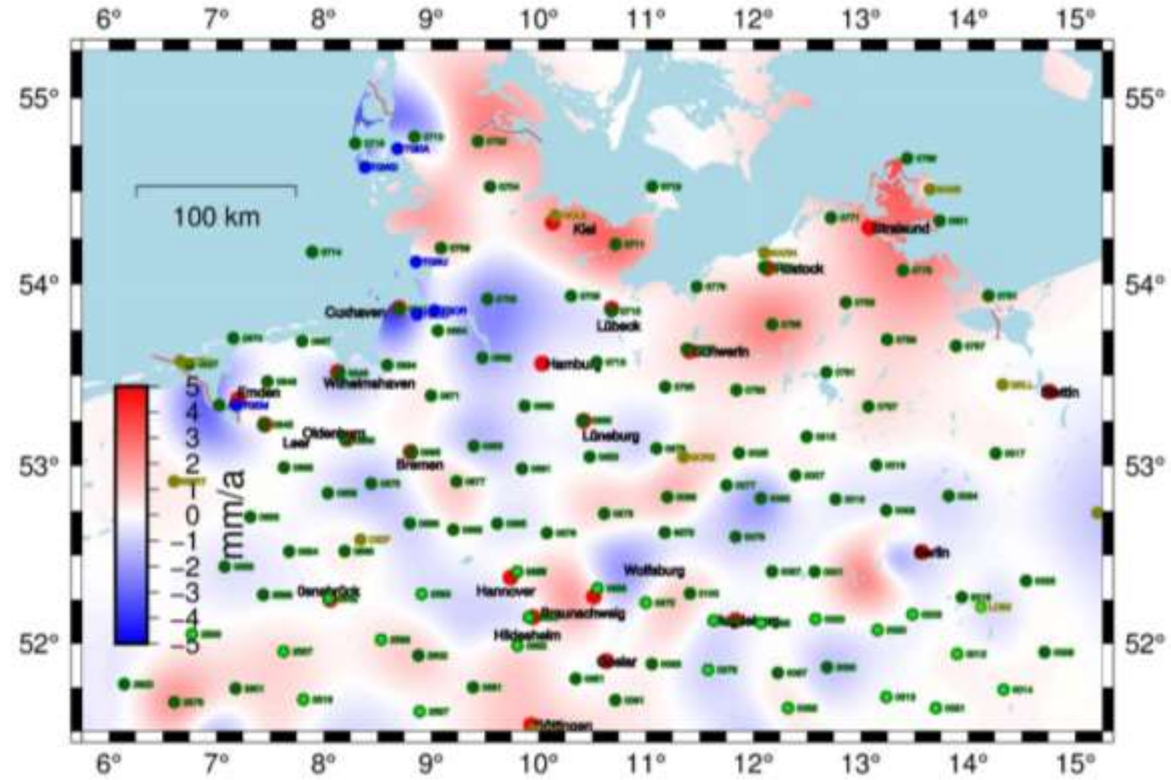

Fig. 7: Velocity field for vertical movements, derived out of GNSS time series 2010 - 2016

Close to the border to the Netherlands the results indicate strong subsidence and coincide in a reasonable way with result from the Netherlands, see NCG (2019), taking into account the different time span of observations.

The zones with uplifts in the area of the Baltic Sea fits well to the effects expected by GIA, as discussed in section 3.2 and depicted in Fig. 6. But the absolute amount of movements is over estimated, compared to the global model.

4.3 Modelling with PSI-data

Finally the results of an RBF-based approximation with all PSI-results are presented in Fig. 8 and Fig. 9. This analysis is based on the methods, described in short in section 4.1, in detail in Niemeier et al. (2021). With data available between October 2014 and March 2019 just a linear velocity model could be justified.

All together about 800 000 PSI points were identified and processed, what makes it clear that for the final approximation a reduction of this huge amount of data was necessary. Here a distance based clustering was applied. In addition the position of the RBFs and their standard deviation (range of influence) was computed.

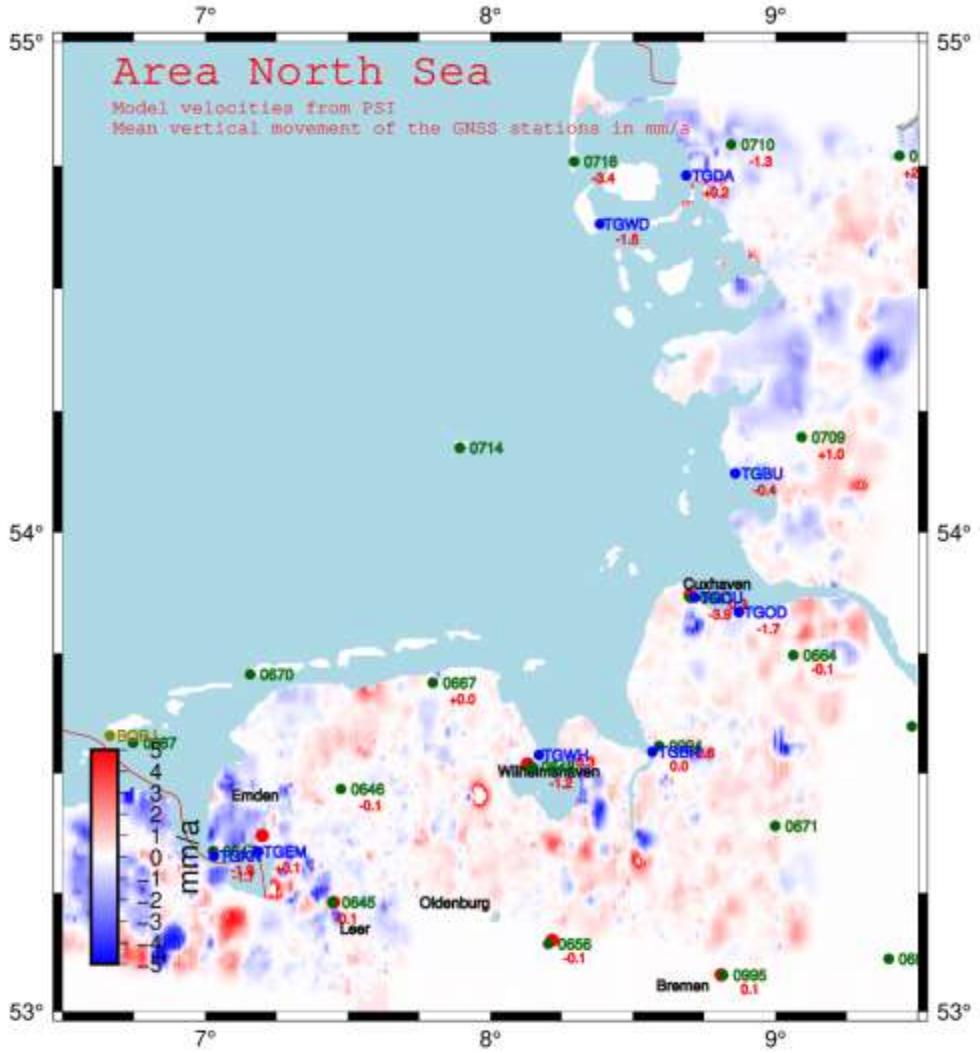

Fig. 8: Vertical movements for Northern Sea in Germany, derived out of PSI data 2014-2019

A direct numerical combination with GNSS data was not successful. In Fig. 8 and 9 the velocities of those GNSS-stations are included, that lie within the PSI study area. One can see that for some stations a good coincidence between GNNS-velocities and PSI results could be identified, but others encountered reasonable differences between both observation methods.

In total this modelling of PSI results show identical tendencies as the GNSS modelling presented in Fig.6, but they are more heterogeneous. This indicates that with radar interferometry even with short observation times a lot of details in the behaviour of a surface can be studied.
A more detailed discussion on this topic in general and a first explanation for some local diplacement pattern are given in Niemeier et al. (2021).

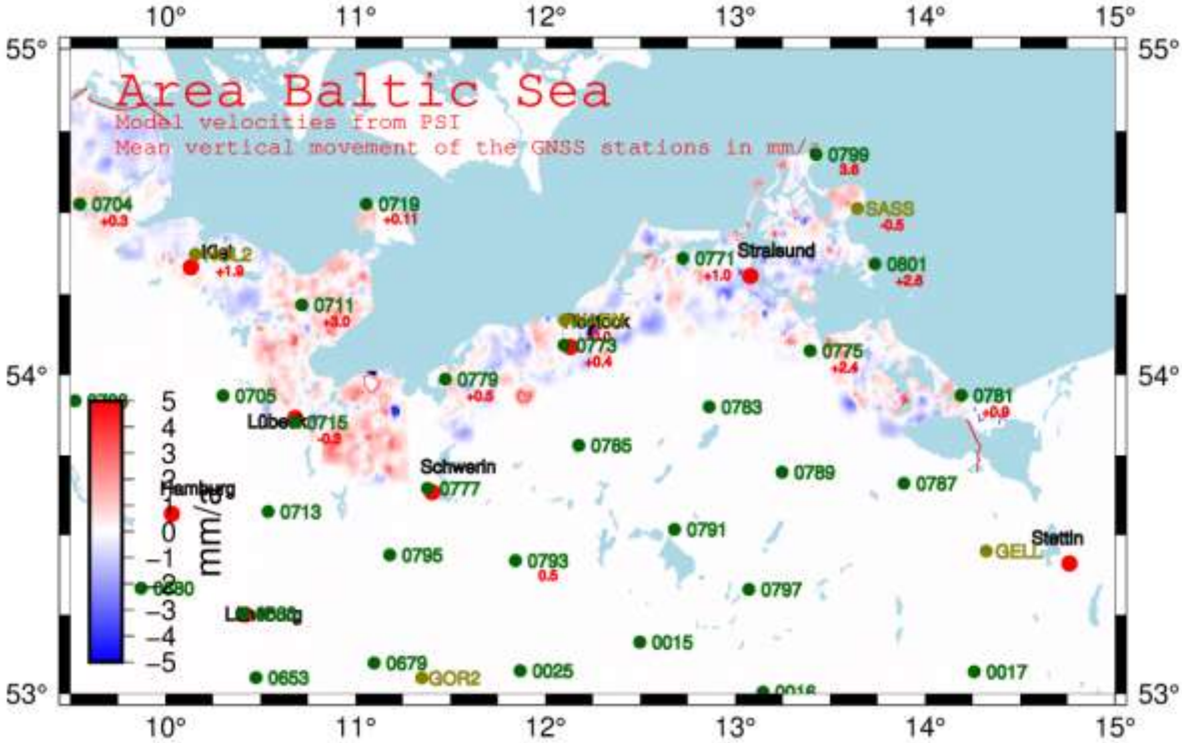

Fig. 9: Vertical movements for Baltic Sea in Germany, derived out of PSI data 2014-2019

5. CONCLUSION

In this research project it was possible to derive vertical movements for all coastal areas at Northern and Baltic sea within Germany. The derived velocity rates can be considered as beeing absolute rates, as they are related to ”stable” areas in the low mountain ranges several 100 km apart.
Even if the time span for taking the observations was relatively short, the results give a realistic picture an the actual vertical movements in the study area. The comparison with external information supports these results and was used here as verification.
The combination of geodetic sensors with different physical principles resulted in some differencen in the derived movement rates, but can be seen as promissing tool for the future to derive reliable results.

Acknowledgement

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